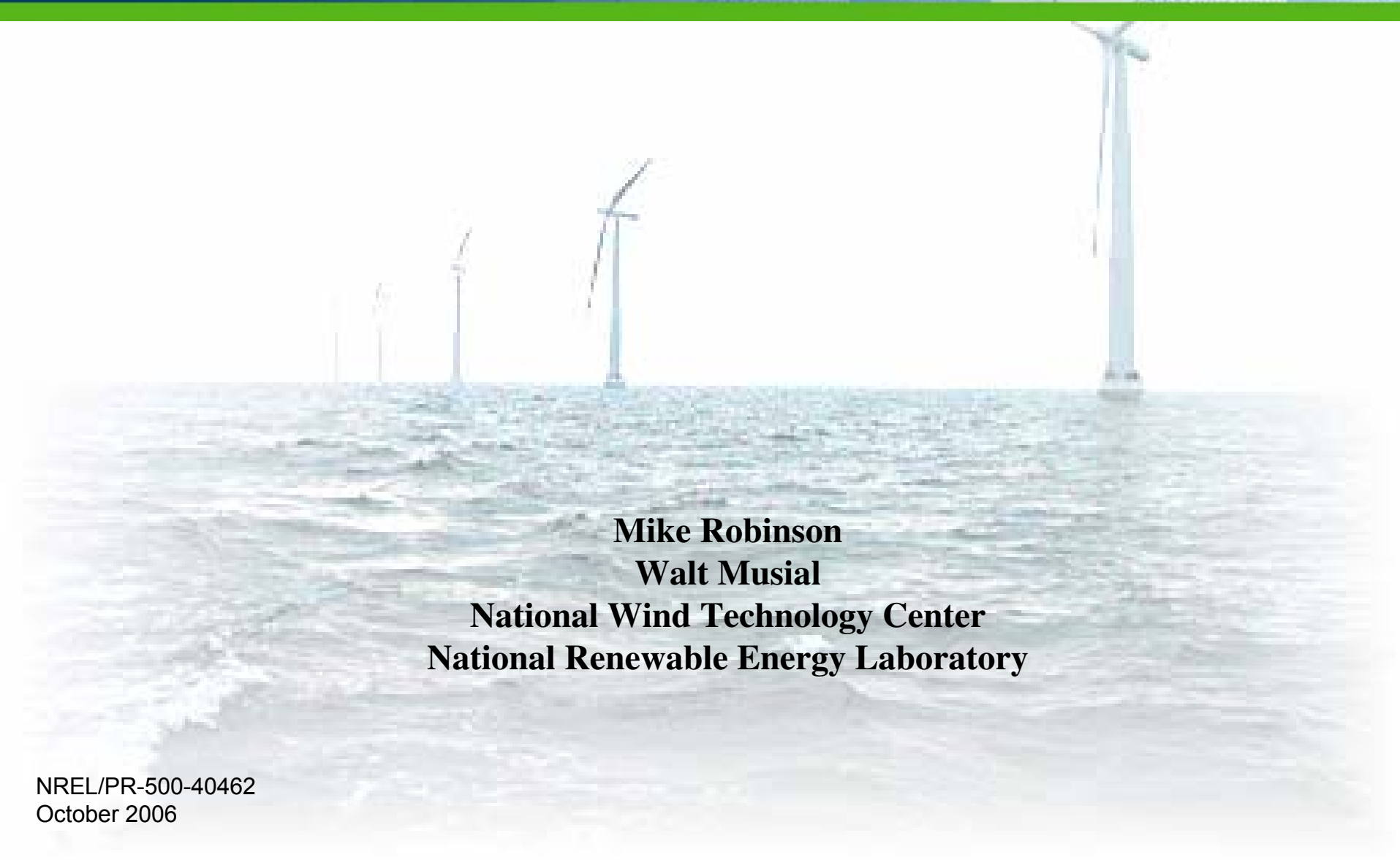




U.S. Department of Energy
Energy Efficiency
and Renewable Energy

Bringing you a prosperous future where energy
is clean, abundant, reliable, and affordable.

Offshore Wind Technology Overview

A photograph of several offshore wind turbines in the ocean. The turbines are white with three blades each, and they are spaced out across the horizon. The water is a deep blue, and the sky is a lighter blue. The overall scene is a wide-angle shot of an offshore wind farm.

Mike Robinson
Walt Musial
National Wind Technology Center
National Renewable Energy Laboratory



U.S. Department of Energy

Energy Efficiency and Renewable Energy

Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

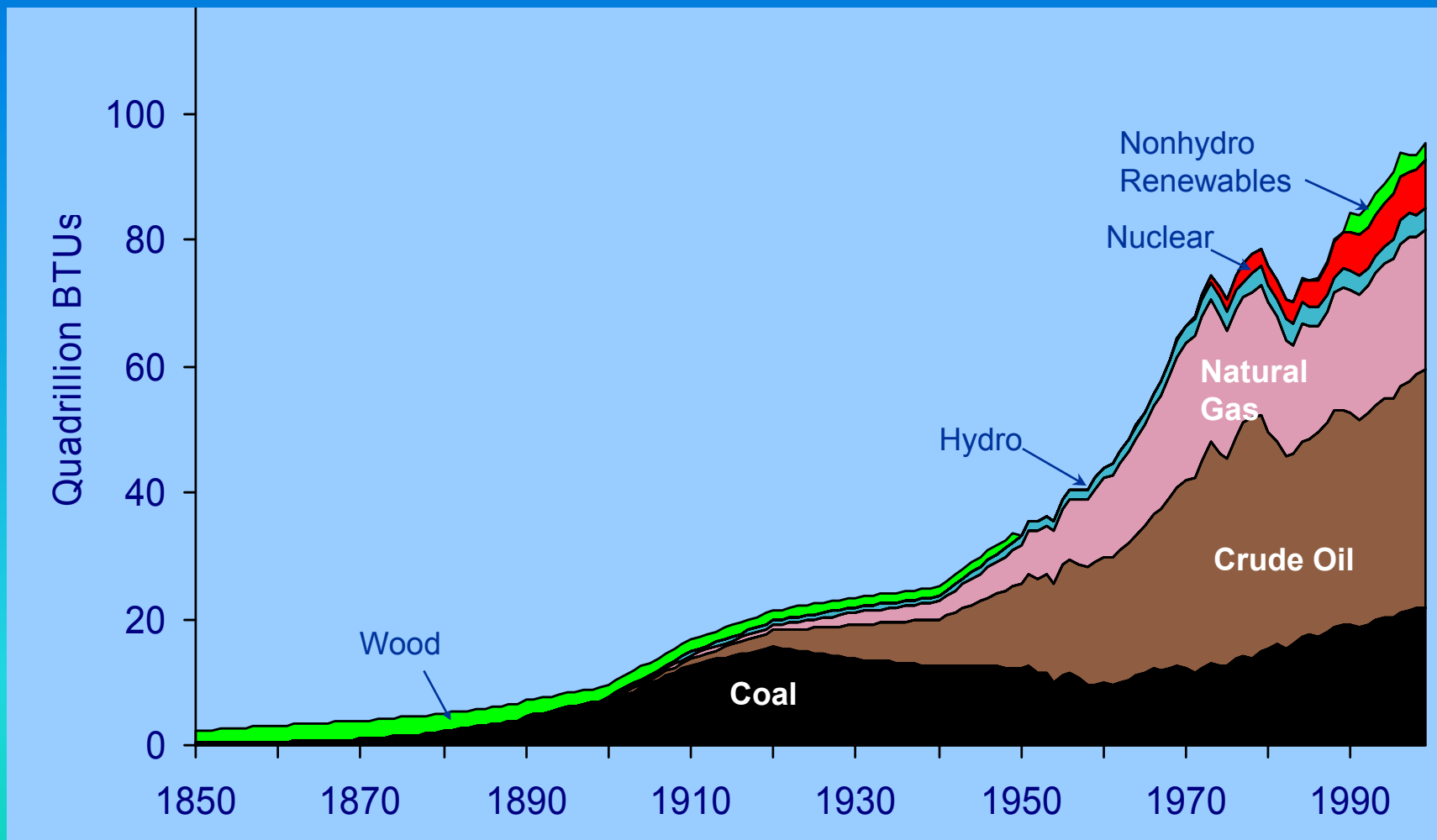
Disclaimer and Government License

This work has been authored by Midwest Research Institute (MRI) under Contract No. DE-AC36-99GO10337 with the U.S. Department of Energy (the "DOE"). The United States Government (the "Government") retains and the publisher, by accepting the work for publication, acknowledges that the Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for Government purposes.

Neither MRI, the DOE, the Government, nor any other agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe any privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not constitute or imply its endorsement, recommendation, or favoring by the Government or any agency thereof. The views and opinions of the authors and/or presenters expressed herein do not necessarily state or reflect those of MRI, the DOE, the Government, or any agency thereof.



The U.S. Energy Picture by Source - 1850-1999

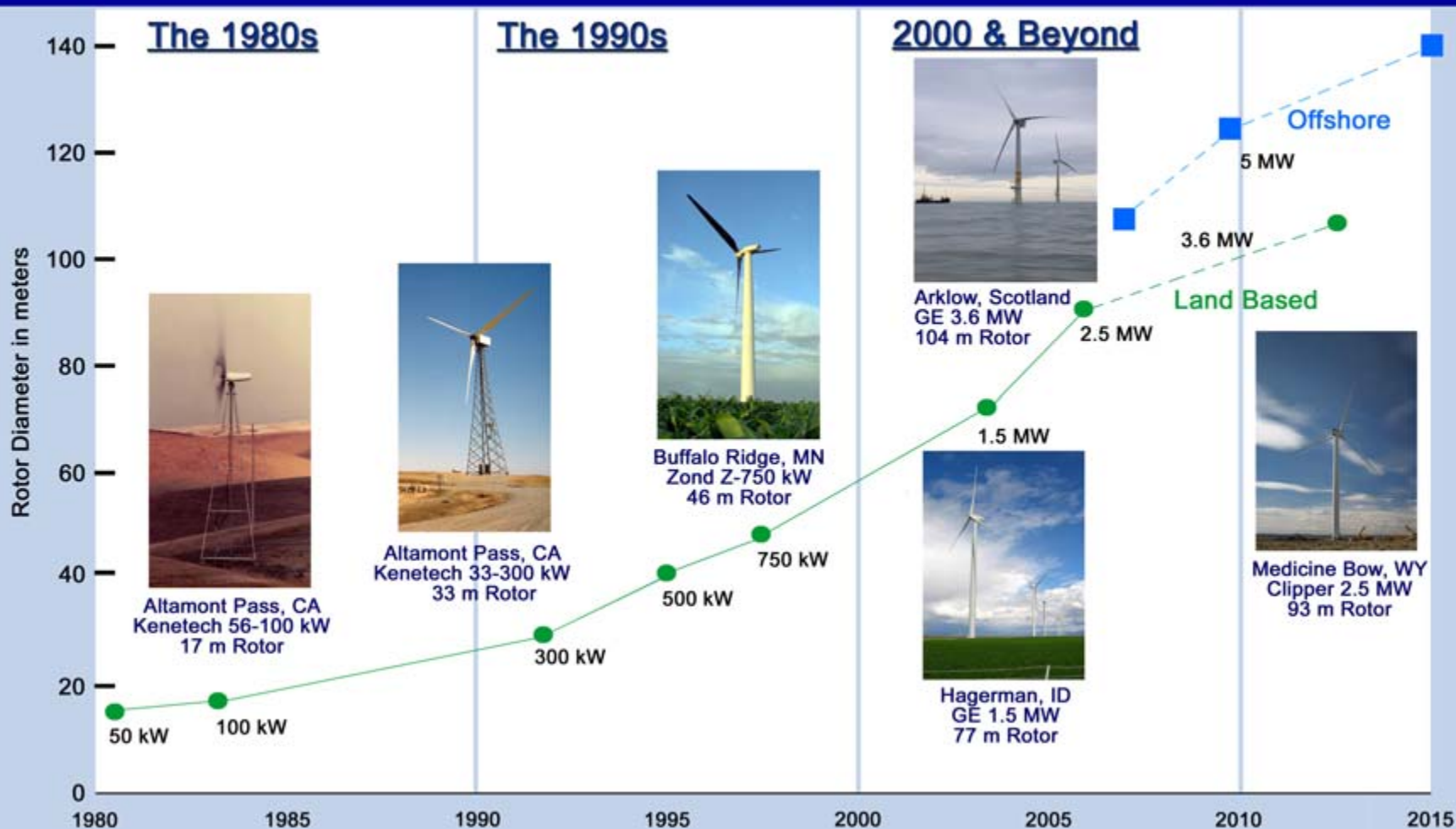


Source: 1850-1949, Energy Perspectives: A Presentation of Major Energy and Energy-Related Data, U.S. Department of the Interior, 1975; 1950-1996, Annual Energy Review 1996, Table 1.3. Note: Between 1950 and 1990, there was no reporting of non-utility use of renewables. 1997-1999, Annual Energy Review 1999, Table F1b.



Evolution of U.S. Commercial Wind Technology

Evolution of U.S. Commercial Wind Technology





Offshore GE Wind Energy

3.6 MW Prototype

- **Offshore GE 3.6 MW**
104 meter rotor diameter
- **Offshore design requirements considered from the outset:**
 - **Crane system for all components**
 - **Simplified installation**
 - **Helicopter platform**

Boeing 747-400





Cost of Energy Trends

1981: 40 cents/kWh

- Increased Turbine Size
- R&D Advances
- Manufacturing Improvements



2006: 9.5 cents/kWh

- Multimegawatt Turbines
- High Reliability Systems
- Infrastructure Improvements

Land-based

2006: 3 - 6 cents/kWh

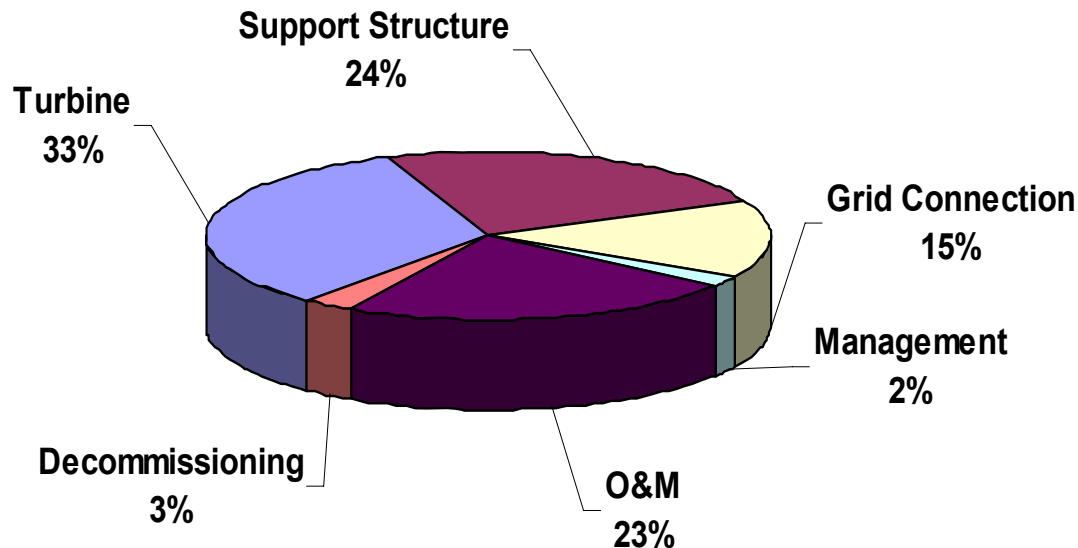
Offshore

2014: 5 cents/kWh



Offshore Turbine Size Drivers

- Offshore Turbines are about 1/3 of total project cost.
- Thus, as turbines grow larger:
 - Foundation costs decrease
 - Electrical infrastructure costs decrease
 - Operational expenses decrease
 - More energy is generated per area.
- Offshore infrastructure is also suited for larger machines.



Offshore Wind - Life Cycle Cost of Energy





Offshore Wind – U.S. Rationale

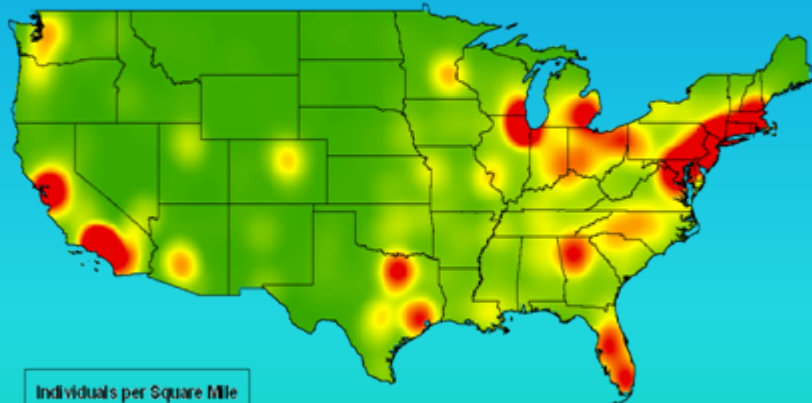
Why Go Offshore?

Windy onshore sites are not close to coastal load centers

The electric utility grid cannot be easily set up for interstate electric transmission

Load centers are close to the offshore wind sites

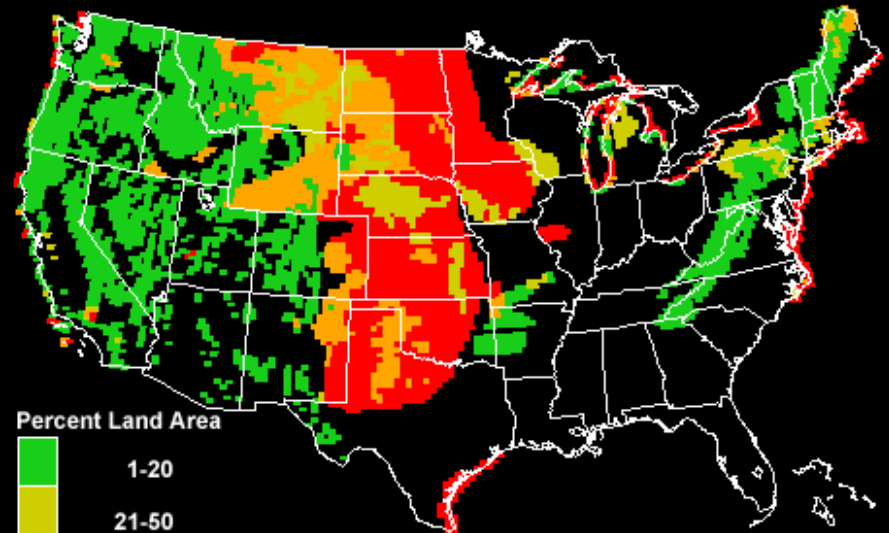
US Population Concentration



Individuals per Square Mile
greater than 1,000
less than 1

Graphic Credit: Bruce Bailey AWS Truewind

US Wind Resource



Percent Land Area

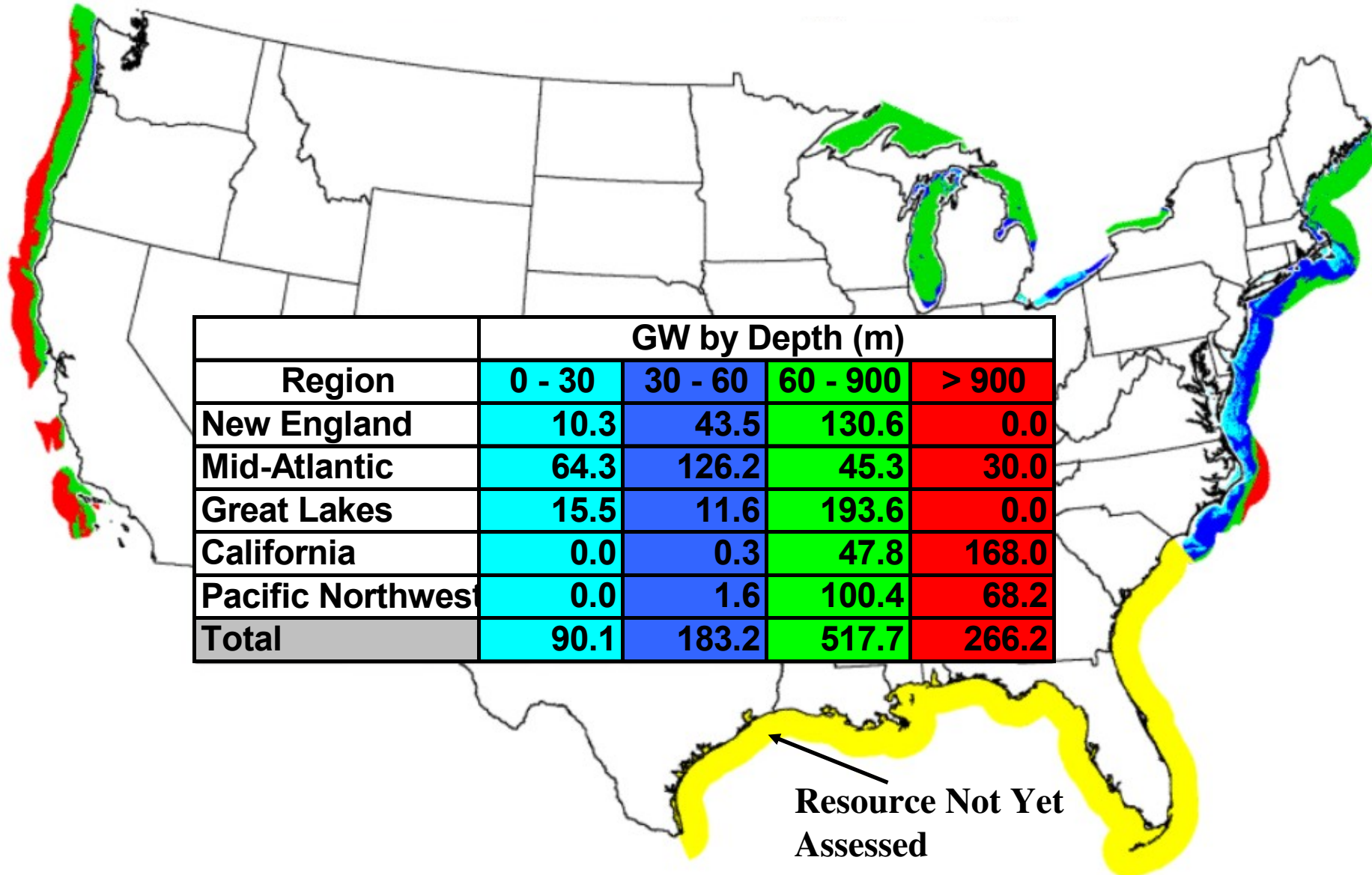
1-20
21-50
51-80
81-100

% area class 3 or above

Graphic Credit: GE Energy



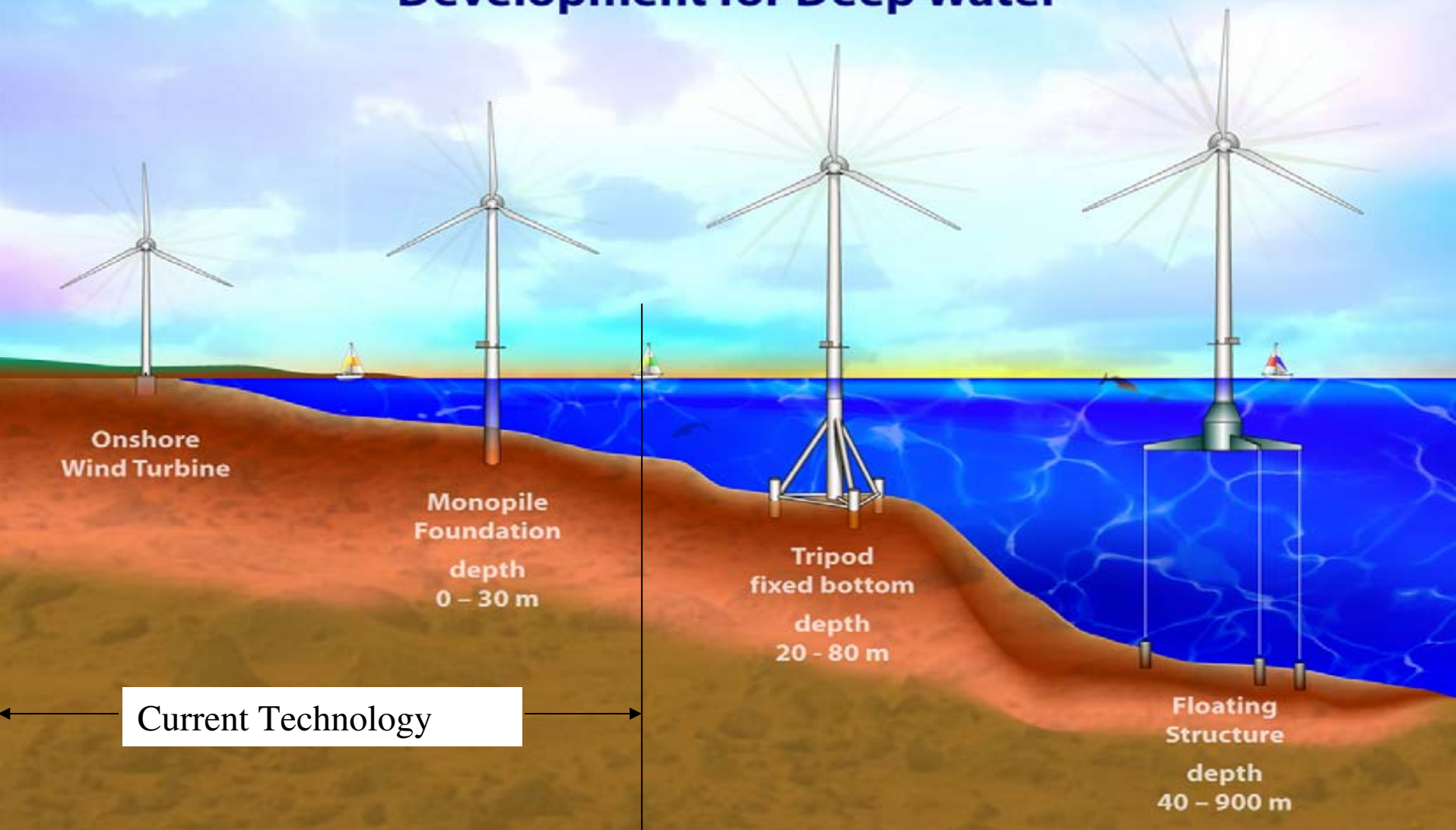
U.S. Offshore Wind Energy Resource





Offshore Wind Turbine Development

Offshore Wind Turbine Development for Deep Water

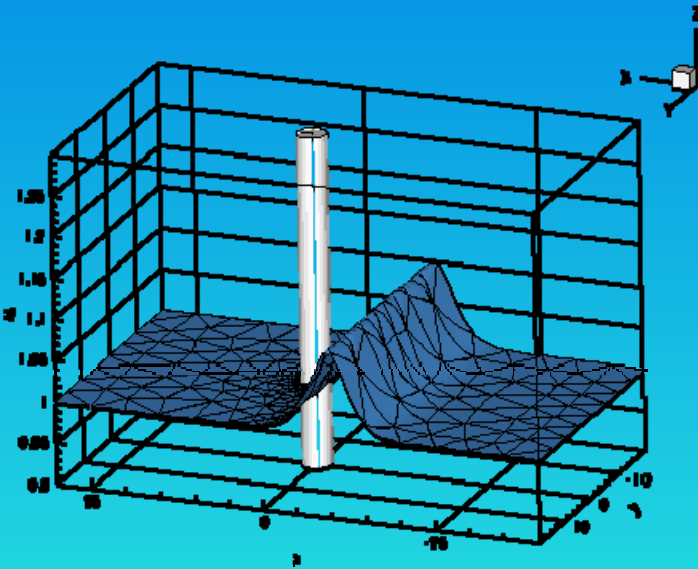




Arklow Banks Windfarm

The Irish Sea

Cable Laying Vessel



Monopile

Transition piece



Fixed Bottom Substructure Technology

Proven Designs



Monopile Foundation

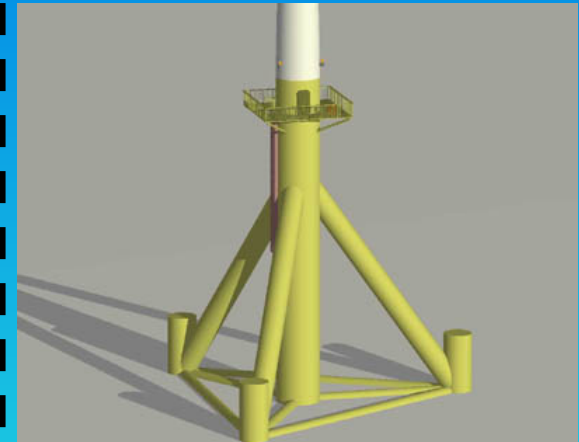
- Most Common Type
- Minimal Footprint
- Depth Limit 25 m
- Low stiffness



Gravity Foundation

- Larger Footprint
- Depth Limit?
- Stiffer but heavy

Future



Tripod/Truss Foundation

- No wind experience
- Oil and gas to 450 m
- Larger footprint



U.S. Department of Energy
Energy Efficiency and Renewable Energy

Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

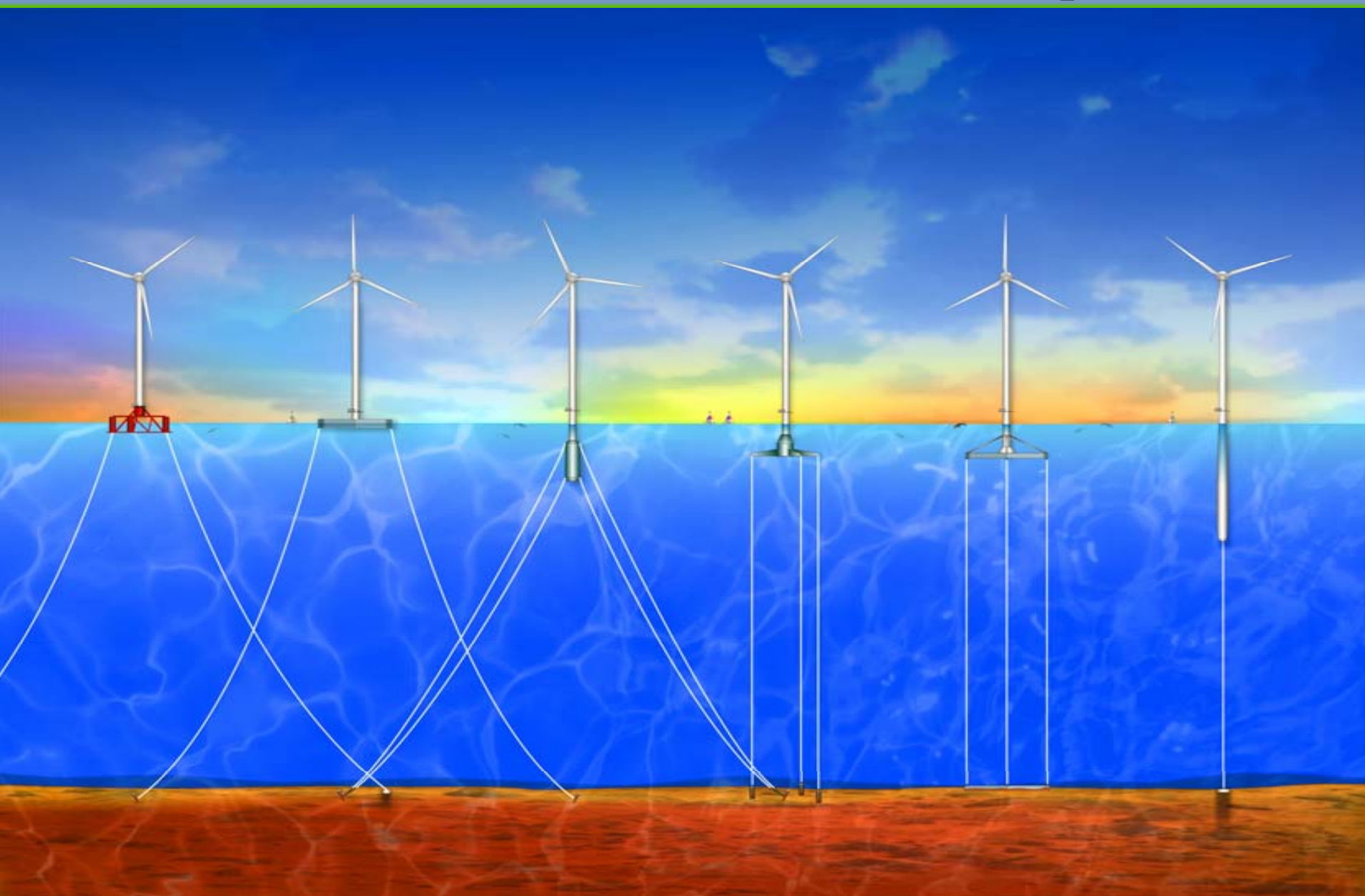
Transitional Depth Foundations 30-m to 90-m Depths??





U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Floating Foundations >60-m Depths





Location of Existing Offshore Installations Worldwide





Enercon 4.5-MW Offshore Prototype



Enercon 4.5MW 112 meter rotor



440 metric tonnes



U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

RePower 5-MW – World's Largest Turbine

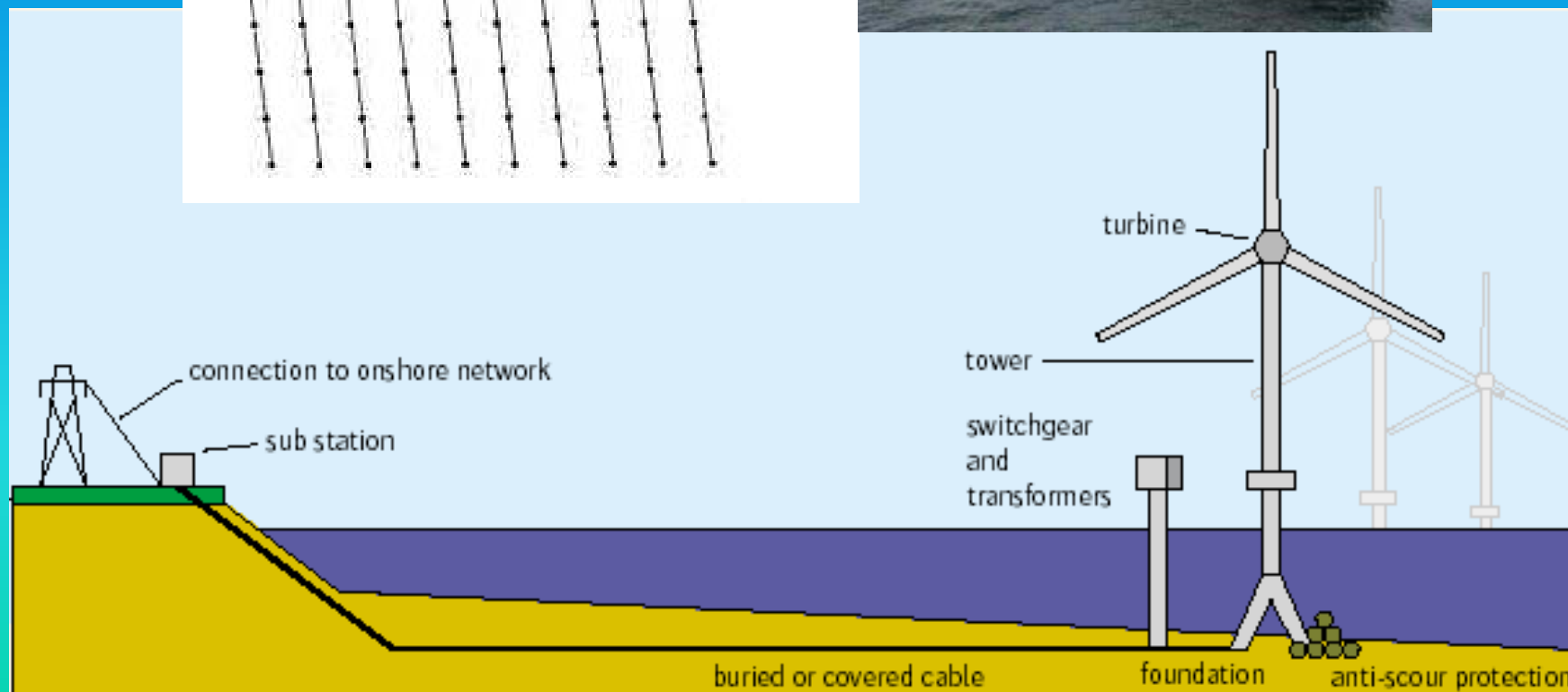
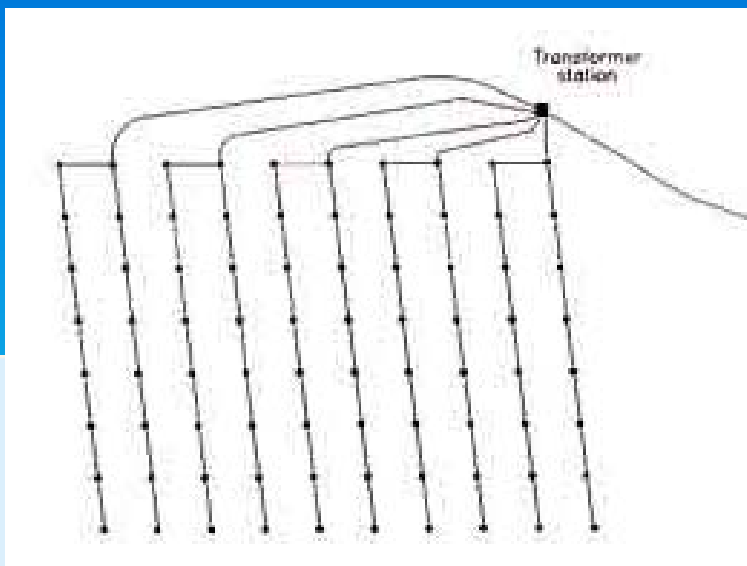


- 5-MW Rating
- 61.5-m blade length (LM Glasfibres)
- Offshore Demonstration project by Talisman Energy in Beatrice Fields
 - 45-m Water Depths
 - Two machines





Typical Offshore Wind Farm Layout



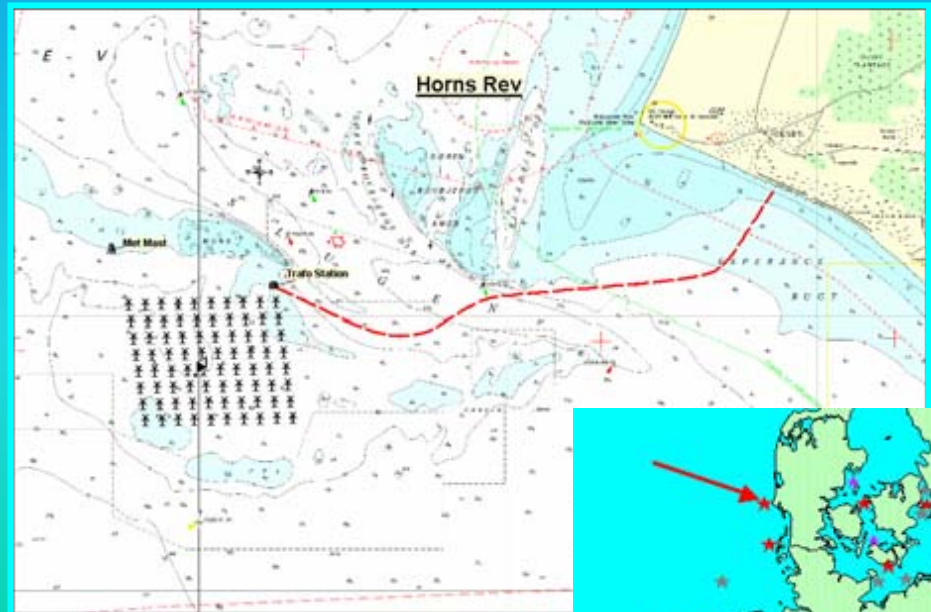


Horns Rev Wind Farm - Denmark



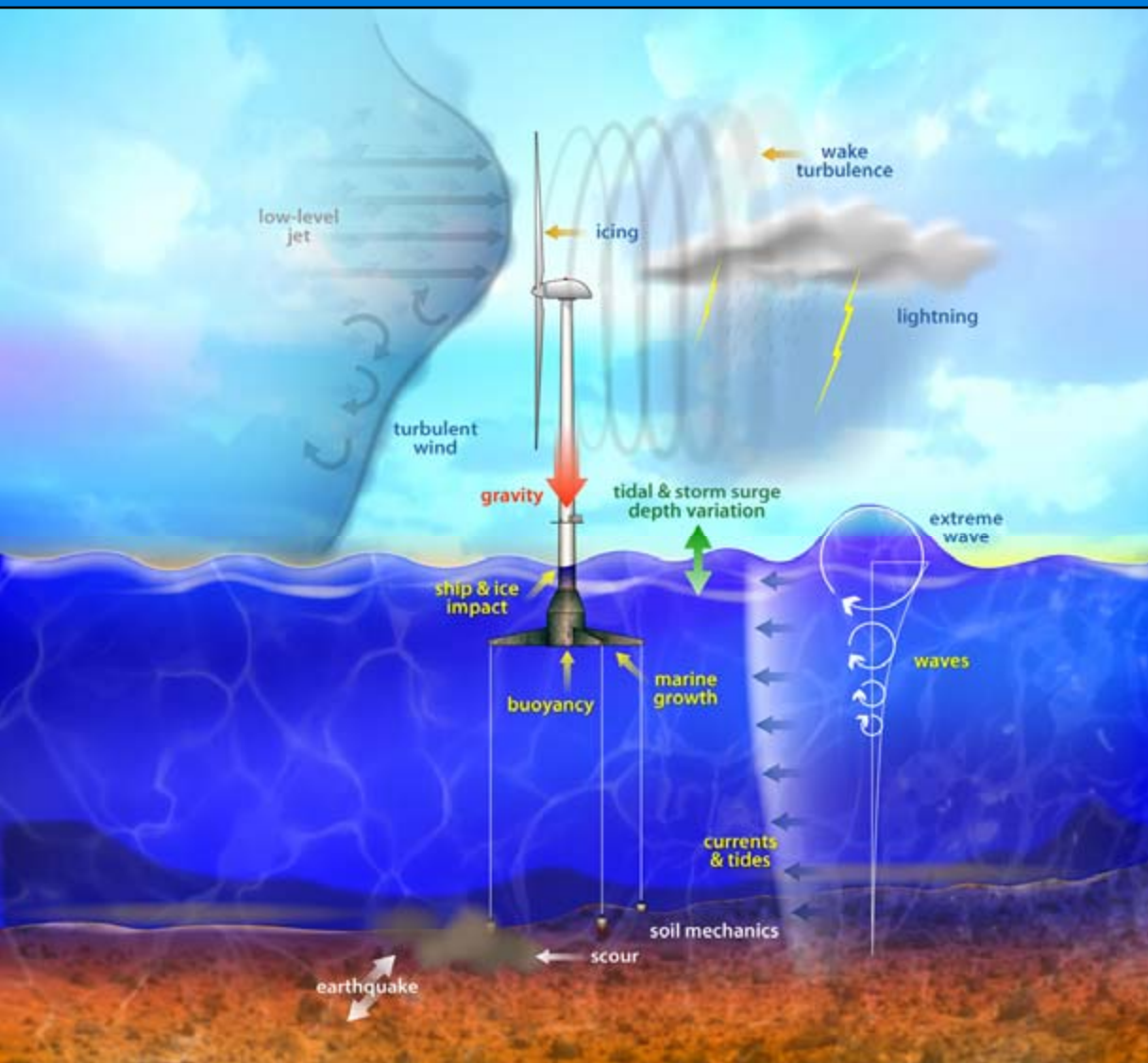
Horns Rev

Country: Denmark
Location: West Coast
Total Capacity: 160 MW
Number of Turbines: 80
Distance to Shore: 14-20 km
Depth: 6-12 m
Capital Costs: 270 million Euro
Manufacturer: Vestas
Total Capacity: 2 MW
Turbine-type: V80 – 80-m diameter
Hub-height: 70 m
Mean Windspeed: 9.7 m/s
Annual Energy output: 600 GWh





Offshore Technical Challenges



Turbulent winds

• Irregular waves

• Gravity / inertia

• Aerodynamics:

- induction

- skewed wake

- dynamic stall

• Hydrodynamics:

- scattering

- radiation

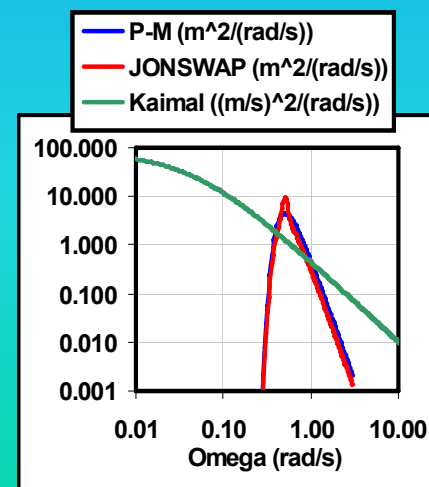
- hydrostatics

• Elasticity

• Mooring dynamics

• Control system

• Fully coupled ex



Wind and Wave Spectra



Offshore Turbine Access



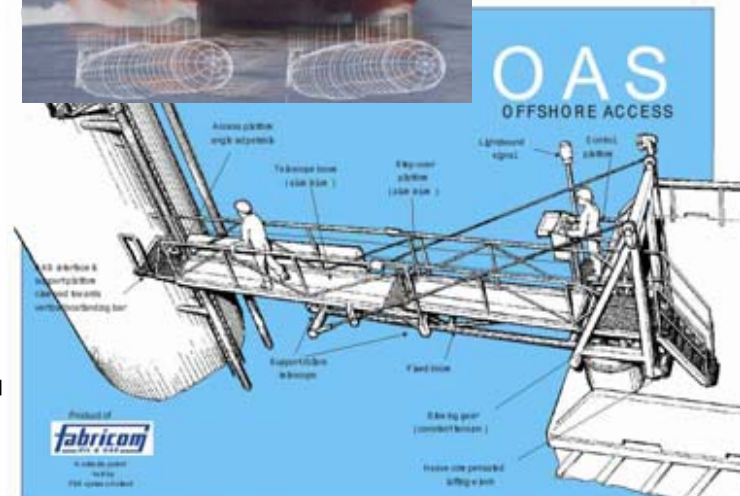
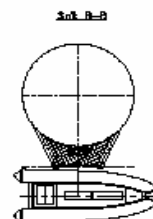
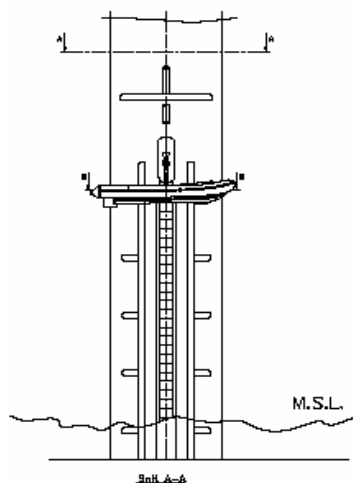
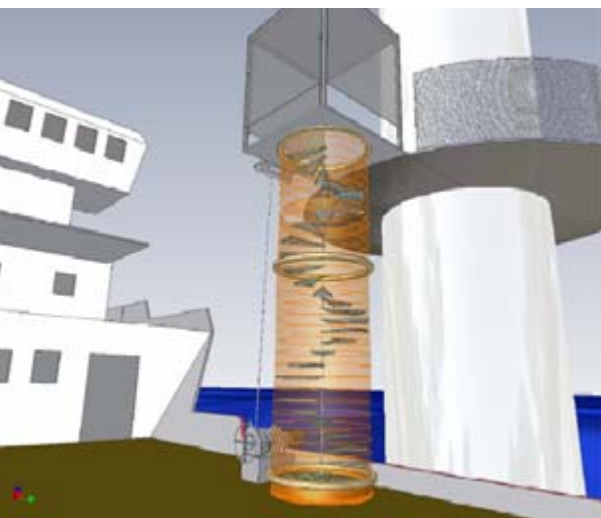
GE Energy



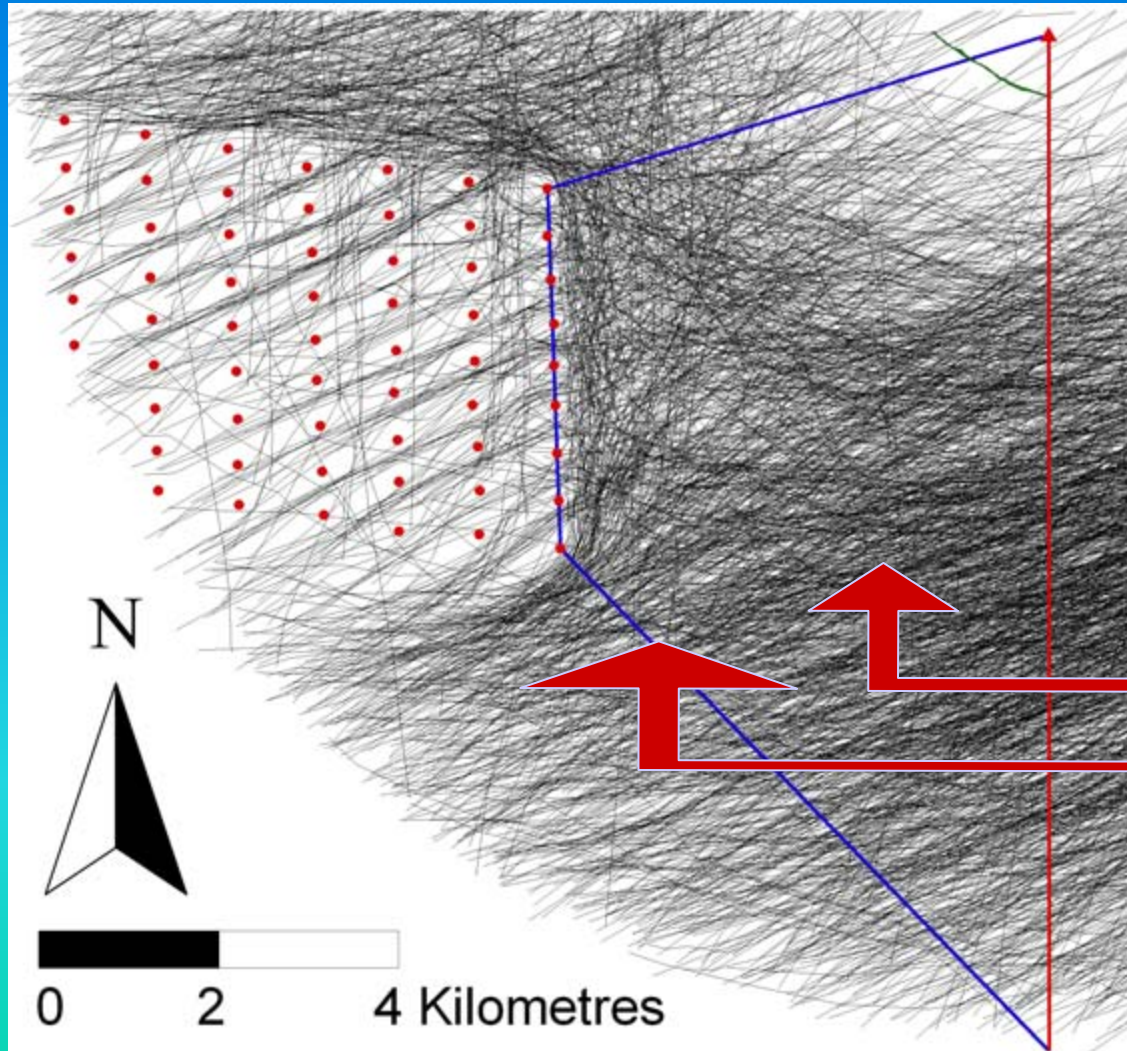
GE Energy



GE Energy



OAS
OFFSHORE ACCESS



Operation (2003):

Birds perceive the presence of wind turbines even in bad visibility

Response distance:

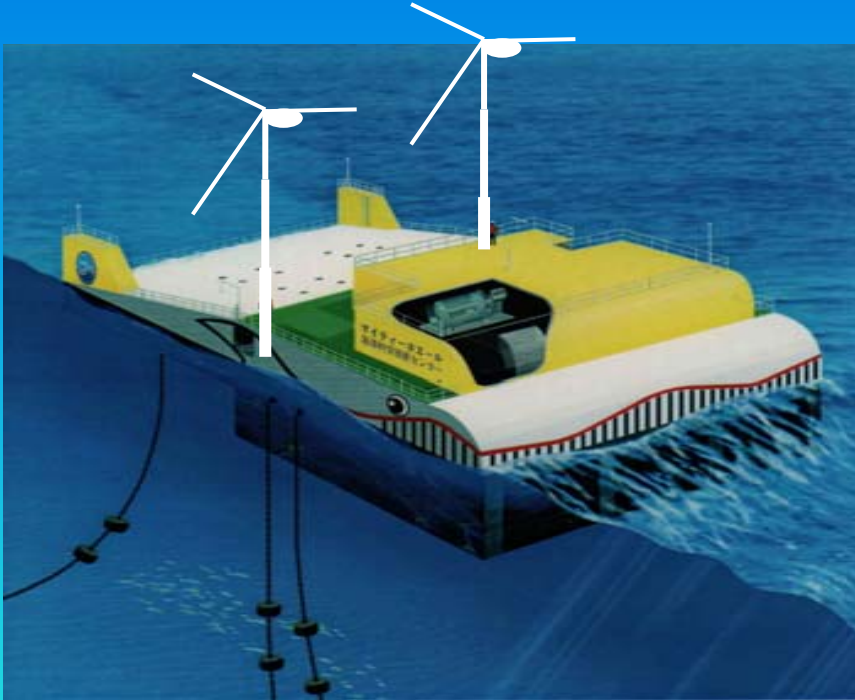
day = c. 3000 m

night = c. 1000 m



Offshore Wind / Wave Synergy

Small Wind-OWC Wave Platform



EPRI Building a Coalition of Developers, Universities and Other Stakeholders to Explore the Wind / Wave Development Potential

- **Common Engineering & Design Considerations**
- **Maximize Grid Interconnect Potential Through Dual Technologies**
- **Improve Intermittency & Total Energy Output**
- **Increase System Reliability & Reduce Maintenance**

Wind / Wave Integrated Platform



Reproduced with permission of Hy-Spec Eng



A Future Vision for Wind Energy Markets

Tomorrow

Today 2005



**Bulk Power
Generator**
4-6¢ at 15 mph

- Land Based
- Bulk Electricity
- Wind Farms

**Potential 20% of
Electricity Market**

Land Based Electricity Path

**Land Based LWST
Large-Scale
2-5 MW**

**Transmission
Barriers**

LWST Turbines:
• 3¢/kWh at 13 mph
• Electricity Market
2012

Offshore Electricity Path

**Offshore Turbines
5 MW and Larger**

**Cost & Regulatory
Barriers**

Offshore LWST Turbine:
• 5 Cents/kWh
• Shallow/**Deep** Water
• Electricity Market
• Higher Wind Sites
2012 and Beyond

**Advanced Applications
Path**

Land or Sea Based:
• Hydrogen
• Clean Water

**Cost & Infrastructure
Barriers**

Custom Turbines:
• Electricity
• H2 Production
• Desalinate Water
• Storage
• Multi-Market
2030 and Beyond